REPORT DOCUMENTATION PAGE

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14. ABSTRACT

Surface plasmon enhanced illumination Is a photonics device that creates a nanometric source of bright propagating light. This light source serves as the basis for a direct write maskless photolithography system. The key progress made on this project is the demonstration of lateral resolution less than 50nm. The lateral resolution corresponds directly to feature size when patterning a photoresist.

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Standard Form 298 (Rev. 8-98)
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Accomplishments

The key accomplishments made on this grant are:

- Fabrication of surface plasmon enhanced illumination devices (SPEI) on the end of a cone polished optical fiber with 40nm diameter apertures. These devices were made with bulls' eye patterns and with hexagonal arrays of apertures.
- SPEI device test results indicate that SPEI has great promise as a lithography technology for direct write systems.
    - The above devices were used to demonstrate lateral resolution of less than 50nm well outside of the near-field.
    - The emission from the devices is semicollimated with a full angle divergence of ~0.5 degree.
    - Concentration of the optical flux of 3x was achieved.
- An improved stage (stepper) has been created for use with SPEI devices. It has not been tested as of the conclusion of this grant.
- A breadboard stepper was designed and fabricated.
- SPEI devices were made for use at 257nm by ETEC in their multibeam system for the creation of masks using electron beam technology. The preliminary results from these devices indicate that the optical flux is enhanced versus unaided apertures and that the ETEC system is less sensitive to variation in the beam location when using the SPEI devices than when using their current system.

The PowerPoint material presented at the Las Vegas Advanced Lithography Program Review meeting are incorporated below to provide more detail on these accomplishments.

Publications:

- Stark, P. R. H., Rinko, L. R. & Larson, D. N. Fluorescent Resolution Target for Super Resolution Microscopy. J. Microscopy 212, 307-310 (2003).

- A poster has been accepted for the work with ETEC for the EIPBN conference in early June 2004.

- Mr. Larson is an invited speaker at the EIPBN conference in early June 2004.

Patents: No patents have been filed based on the work on this grant.

Slide 1

Maskless Lithography with Surface Plasmon Enhanced Illumination

Presented to DARPA ALP

Las Vegas

February 4, 2004

Channing Moore, Peter Stark and Dale Larson

Technology Engineering Center

Harvard Medical School

Slide 2

Characteristics of SPEI devices critical to lithography are:

- Small illumination spot diameter: <50nm has been demonstrated with a 40nm aperture and 5-10nm apertures are possible w/current mfg methods.
- Emitted light is propagating, not evanescent
- Up to 3x concentration of the transmitted light has been achieved.
- Illumination spot size is independent of wavelength. Devices for 257nm, 405nm and 558nm have been made.
- SPEI technology is compatible with immersion lithography.

Slide 3

Surface Plasmons?

- Surface Plasmons (SPs) are collective oscillations of electrons in a material (usually a metal) confined to the surface of that material and the space immediately adjacent.
  - In materials displaying metallic behavior, valence electrons behave as a gas and are free to move about spatially without regard to nuclei locations.
  - SPs are similar to bulk plasmons but are of a different frequency due to damping by the surrounding material.

Slide 4

SPEI architecture

Single hole in a conductor

QuickTime™ and a Microsoft Video 1 decompressor are needed to see this picture.

$a_0 = \lambda(\varepsilon_1+\varepsilon_2)/\varepsilon_1\varepsilon_2)^{1/2}\ \zeta$

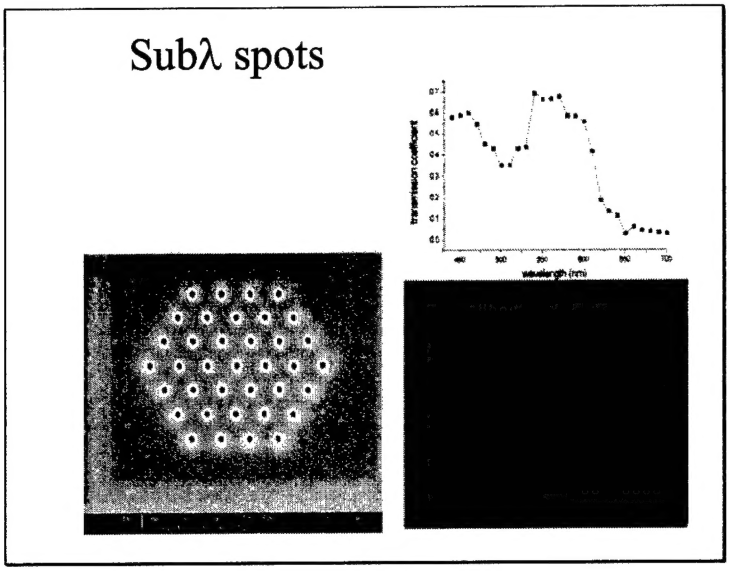
Multiple resonant holes in a monometallic film

where ζ is an integer

The images in this slide are animations that are incompatible with printed formats. Short summaries of each animation are provided below.

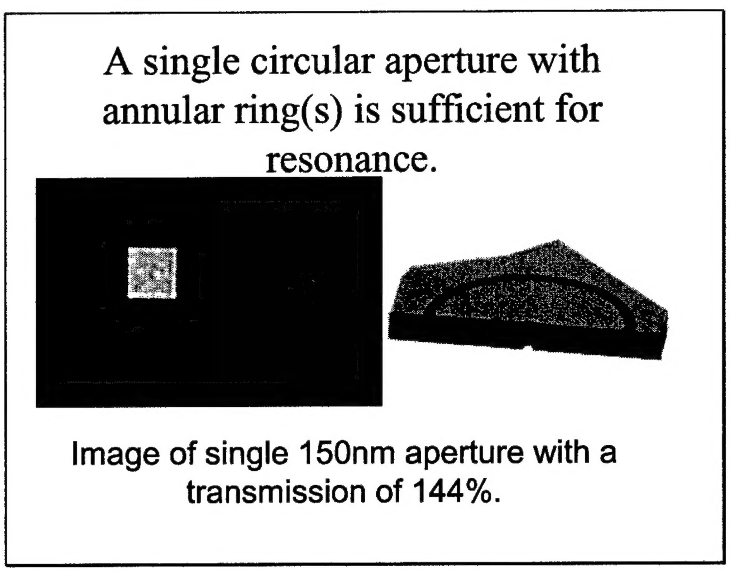
- Single hole in a metal film (upper left hand corner) represents a single unaided aperture. In this situation the majority of the light is reflected and a very small portion (10^{-7}) is transmitted as evanescent light. An example of this case is a near-field scanning optical microscopy probe.
- Multiple holes in a monometallic film can be placed such that photons are able to couple to plasmons via grating momentum. This architecture achieves extraordinary levels of transmission but the light is emitted from the surface and therefore this device does not result in a subwavelength light source.
- The SPEI architecture uses the same phenomenon as the previous architecture but the device is designed such that the coupling conditions on the emission surface are very different from the coupling conditions on the illumination surface. This results in the emitted light being constrained to the aperture, thus creating a subwavelength light source that also has high optical transmission.

Slide 5



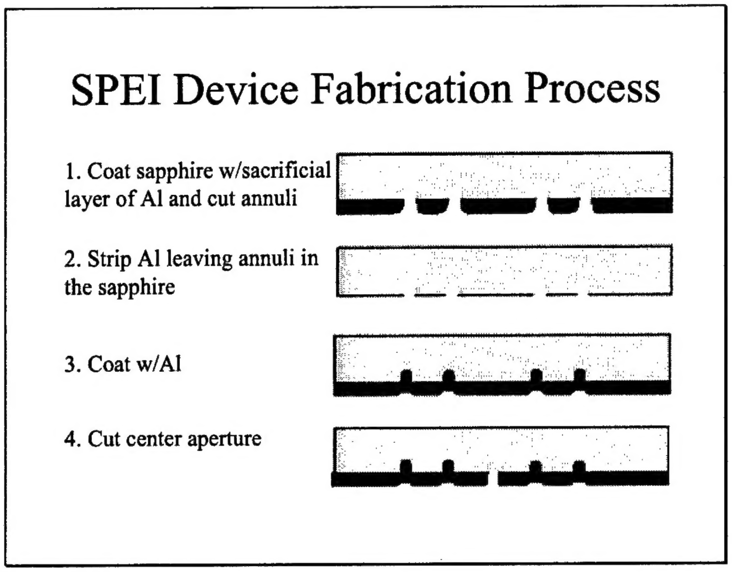
An ion image of an hexagonal SPEI array of 150nm apertures, with a transmission spectrum and an image of the emitted light.

Slide 6



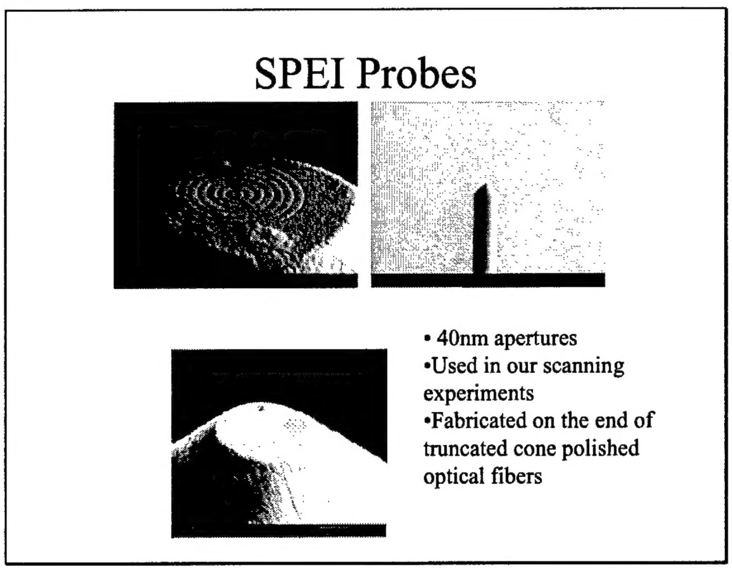
SPEI devices can also be made such that there is a single emitting aperture in the device. For a full scale photolithography system an array of these devices would be fabricated on a solid substrate and independently shuttered to write the pattern in parallel. Initial calculations indicate that an array of 40,000 such devices can pattern a 300mm wafer in ~45 minutes.

Slide 7



This is the process used to fabricate the devices shown in the next slide.

Slide 8

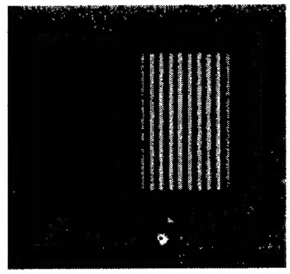


Slide 9

Illumination Spot Size!

Results:

- **Scans located 95nm features on 100nm half pitch**
- **Scans with single aperture and multi-aperture probes reveal 52nm resolution at a distance of greater than 350nm from the target.**
- **These suggest a divergence from the aperture (40nm nominal) of less than 1degree half angle!**



Resolution Target:
Fluorescent polymer removed w/Ion beam milling to create 100nm wide grooves on 195nm centers.
J. Microscopy, **212**, pp 307-310.

Slide 10

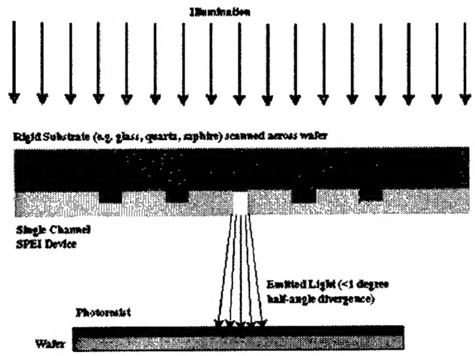
Summary of Scan Data

- 95nm features separated by 100nm resolved
- Fast Fourier Transform of single aperture scan indicates a <50nm illumination spot size
- Fit with simulation for hex array scan indicates a 52nm illumination spot size at distance greater than 350nm
- Fast Fourier Transform of hex array scan indicates a <50nm illumination spot size
- Divergence angle is ~0.5 degree (full angle)

Slide 11

An array of SPEI devices on a rigid substrate will be scanned over the wafer.

Single SPEI device (bulls eye design).



An array of these devices will be fabricated on a solid substrate which will be scanned over the wafer with the emission from each device shuttered on/off to write the pattern.

Slide 12

Use of SPEI for Mask Making

- Collaboration with ETEC established to evaluate the use of SPEI devices in their multi-ebeam system.
- Objectives:
  - to address impact of beam walk
  - to create smaller electron beams

The ETEC system is currently susceptible to positional drift of the illumination beam. The hypothesis is that using SPEI devices will desensitize the system to this variation because the SPEI device will "collect" photons over a large area and channel them through the emitting aperture in a bulls' eye pattern device (see slide 8, the image in the upper left hand corner and slide 13 below). Additional proposed benefits for using the SPEI device in this setting are the ability to excite electrons on the electron emitter material at a smaller diameter thereby reducing the focusing required from the electron optics, and increasing the intensity with the "photonics funnel" effect to achieve a higher density of electrons and therefore a faster writing rate.

Slide 13

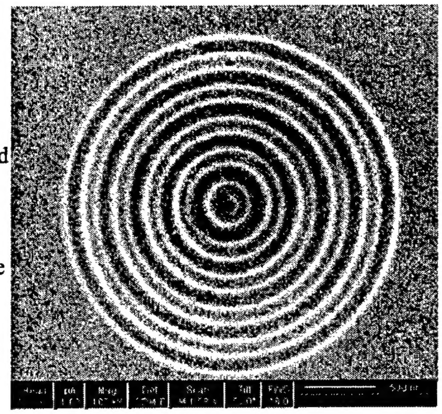
Ion image of a SPEI device for ETEC

35nm thick coating of Al on saphire blank

a_0=224nm, designed for 257nm illumination

Annuli 100nm wide

Central aperture 100nm diameter



Slide 14

Preliminary results are encouraging.

- ETEC data show that output is less sensitive to beam walk.
- More light than expected from diffraction theory is emitted from the subwavelength SPEI apertures.

Slide 15

Next steps with ETEC

- ETEC currently examining the SPEI devices using SEM
- Coat SPEI devices with photoemitter and evaluate the resulting electron beams
- More devices will be made as necessary

Slide 16

Next Steps

- Short-term:
  - Repeat the illumination spot diameter experiment (new stage and resolution target designs)
  - Contact holes in h-line resist
  - Continued support of ETEC
- Long-term:
  - More patterns
  - Assess process latitude
  - Improved SPEI devices
  - Scale-up issues